TECHNICAL ARTICLES AND PAPERS

THE S-1 SERVO SYSTEM

A GENERAL DESCRIPTION AND ANALYSIS

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INTRODUCTION

The Photocircuits S-1 Servo System is a device which incorporates a Printed Motor or a Minertia Motor and a DC Servo amplifier in such a way as to maintain an extremely high degree of accuracy with respect to motor shaft speed and instantaneous position in the presence of disturbing torques.

It will be shown that very wide speed ranges, large torque loads and disturbances, and a wide range of inertial loads may be handled with the basic system by appropriate manipulation of the design variables.

Detailed specifications for standard systems of this type are available in separate literature. Of necessity, the standard systems impose design limitations and tie down the operating parameters so that specific numbers can be assigned to the points of interest within the torque ranges available in the standard line. The use of specific numbers in this way to describe "typical" systems allows one to grasp more clearly the nature of the device and what it can do under a prescribed set of conditions.

As a practical matter, however, there are many motor control requirements which, for one reason or another, fall outside the restrictions imposed by the standard systems line. Fortunately or unfortunately, depending upon the point of view, the versatility of the device is such that a vast number of applications in diverse fields with different problems to solve can be handled with essentially the same basic system with minor modifications in most cases. For this reason, it is virtually impossible to list specifications covering all possible situations.

In order to alleviate this problem, this paper has been prepared mainly as an aid to the designer. It covers various aspects of the system quite thoroughly and describes the inter-relationship between the system variables so that one is better equipped to determine feasibility, predict performance and accuracy, and generally optimize a proposed design.

GENERAL DESCRIPTION

In principle, the S-1 System may be considered as the DC equivalent of an AC synchronous motor locked to the 60 cycle power line frequency; the similarity being that an accurate reference control frequency determines the absolute synchronous speed of the motor in the S-1 servo, just as the power line frequency controls the speed of a given AC synchronous motor. In practice, however, the similarity ends here. For example, the servo system may be thought of as being roughly equivalent to a 2000 pole AC motor with a speed control frequency range typically from 1 KC to 100 KC. This, of course, is not practical in a true AC system. Further, the phenomenon known as hunting is very often a limiting factor in the AC synchronous motor since it is usually not practical to provide really effective stabilizing or damping controls for such motors. It is relatively simple, however, to meet the requirements of unconditional stability and to provide critical damping by electronic means with the servo approach.

The three basic elements of the package are the motor and pick-off device, the servo amplifier, and the power amplifier. These will be discussed in the following sections. The power supply and input reference frequency devices are considered as elements external to the servo, and are usually not supplied with the system, however their general requirements are covered below.

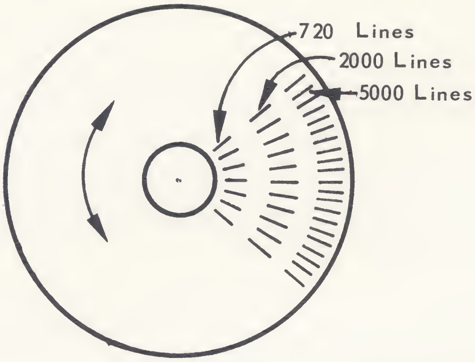
As indicated, the speed of the motor is set by adjusting the frequency of the reference oscillator. Upon applying power to the system, the bi-directional power amplifier is saturated in one direction and the motor accelerates under full power until the frequency of the reference source and the frequency (which is proportional to motor speed) obtained from the motor pick-off device are exactly equal. At this point the two frequencies are "locked" together on a pulse for pulse basis; a condition which may be thought of as two "electronic gears" in mesh. Once synchronous speed is achieved, servo control is thereafter obtained by continuous monitoring of the phase angle or relative position of the reference and feedback (pick-off) frequencies and using the resultant error signal to control the motor shaft position. System load disturbances will cause corresponding phase angle changes which in turn initiate restoring torques at the motor shaft in proportion to both the magnitude and the rate of change of the phase shift. In essence, the above describes a two step operation requiring a synchronous acquisition system and a phase comparator. The motor will now run under stable synchronous phase control conditions in the presence of any torque disturbances which fall within the torque (current) correcting capabilities of the system.

If, now, it is desired to change the motor speed, the frequency of the reference source may be altered (this may be either a switched or a continuously variable adjustment) and the system will accelerate or decelerate until synchronism and phase control is obtained at the new speed. As discussed in the section on system limitations, considerable accelerating and decelerating torques are available and speed changes may be very rapid for low inertia systems.

Motor/Tachometer

The motor used in the S-1 servo system may be any of those in the P.M.I. Printed Motor line covering a range from the 2 3/4" diameter device (PM-258) delivering 1 oz-in of torque per ampere, to the 13 1/2" device (PM-13510) delivering 100 oz-in of torque per ampere. The S-1 servo is also adaptable for use with P. M. I. Minertia Motors which have ratings up to 8 h.p. All of these motors may be controlled with the same basic servo, the only differences being in the required capacity of the power amplifier and the external power supply. Detailed motor data is available in separate literature.

The pick-off device is an accurate optical system which is mounted as an integral part of the motor and serves as a digital tachometer. It consists of a coded glass disc mounted on the motor shaft and a photoelectric readout assembly including a lamp, lens, grating, solar cell array, and suitable mounting hardware and adjustments. See Figure 1.



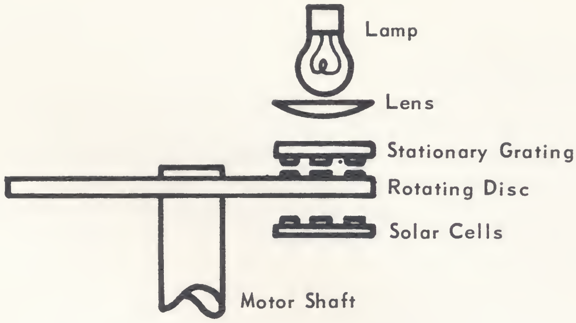


FIGURE1

The grating is a small glass section coded with the same information as that on the disc. As the disc rotates with the motor shaft, the solar cells pick up the information generated by the lamp and the interference pattern set up between the disc and the stationary grating. The coding on the disc is in the form of concentric rings within which are a number of equally spaced radial opaque (black) lines. A typical standard disc has three such coded tracks with respectively 5000, 2000, and 720 lines. The choice of optimum track density is based on an analysis of the overall system requirements, and will usually fall within the range of 100 to 5000 lines per revolution.

When a track is selected (only one track is used at a time) the solar cell which is positioned under the track will see a cyclic change from dark to light. The geometry of the system is such that the output from the cell is a sine wave requiring an angular movement of the disc equivalent to one line and one space per output cycle. Thus the 5000 line track will produce an output signal of 5000 cycles per revolution of the motor shaft. Since synchronous operation requires that the frequencies from the reference and pick-off be exactly equal, it follows that the absolute motor speed may be determined from the relationship:

$$\text{Speed (RPM)} = \frac{\text{Reference Frequency (cps) x 60}}{\text{Pick-off Density (Lines/Rev)}}$$

It should be noted that if the digital tachometer output signal is accurately converted to a series of short duration pulses, this information, when compared with the reference signal is a true indication of both motor speed (frequency) and instantaneous shaft position (phase angle). This information comprises the servo feedback signal used to control the motor.

The actual output from the solar cell is a high impedance signal in the range of about 10 - 80 mv/peak-to-peak, depending upon the track density, motor speed, and the optical system adjustments. Since this is a low level signal subject to various types of noise pickup, especially when long cables are required, a DC coupled preamplifier is mounted on the motor case as part of the assembly. This module loads down the solar cell so that it operates as a linear current device (with respect to light intensity) and provides a low impedance output at a minimum level of about 150 mv peak to peak.

Servo Amplifier

The servo amplifier consists of a printed circuit board on which are mounted eight small solid-state encapsulated modules and a small number of miscellaneous components. The assembly is provided with contacts and a multi-pin board connector. It is the purpose of the servo amplifier to compare, on a time basis, the signals from the input reference frequency generator and the motor pick-off device, to process this information, and to convert the result to an appropriate DC level which is passed on to the power amplifer and thence to the motor.

Included in the modules are an amplifier-limiter for the pick-off signal, a dual trigger circuit to shape the reference and pick-off input waveforms, three logic modules containing synchronous acquisition circuits, an operational amplifier with a removable feedback module to establish system gain and frequency characteristics, and a low level driver amplifier to feed the external power amplifier. Low level decoupling and zener diode networks are also included. The package measures approximately 4 x 6 1/2 x 7/8 inches.

Power Amplifier

The power amplifier used with the S-1 system is a straight-forward push-pull class B solid state device capable of supplying large bidirectional currents to the motor armature. The components are mounted on a circuit board and heat sink.

The requirement for bidirectional currents is not so that the motor may be run in either direction (this may be done simply by reversing the motor leads), but rather that the servo can control or drive the motor with full power under conditions requiring either acceleration or deceleration; the implication being that either positive or negative (overhauling or "speed-up") torque disturbances are kept under "symmetrical" servo control. This includes both long term and instantaneous loads and disturbances and insures, for example, that the motor will drive rather than coast to a new condition when the speed is switched downwards.

The question of output transistor power dissipation, temperature derating, and circuit protection is a subject in itself, and falls outside the scope of this paper. Other Photocircuits technical literature has been prepared to cover these points, and shows conditions under which it is desirable to use two or even three power amplifiers connected in parallel, particularly when large motors requiring very heavy currents are employed.

Reference Frequency Source

The requirements for a reference frequency oscillator will vary considerably depending upon the long term accuracy needs, speed range, and whether discrete speeds or continuously variable speeds are used. In practice, systems have been designed using reference frequencies covering the range of 50 cps to 100 KC. Crystal controlled oscillators together with currently available low cost binary dividers make excellent control devices where system speeds have a 2:1 relationship. Tuning fork oscillators have been used, and in some cases an audio type signal generator or even a transistor feedback or unijunction oscillator will suffice. Because there are so many approaches to the reference frequency source problem and since many complete systems already contain a suitable device, Photocircuits does not normally supply the reference with the S-1 Servo System. The basic requirement in any case is for a square wave output with a minimum level of about 2 volts peak-to-peak.

Power Supply Requirements

For essentially the same reasons cited previously, Photocircuits normally does not furnish a power supply with the S-1 system, although there is one unit available separately under the designation SKC-1107 and is suitable for many applications.

The usual approach to the power problem is to use a "brute force" stacked supply in the range of ±15 volts DC with respect to common (ground). This type of supply requires a center-tapped power transformer, a bridge rectifier, and two large filter capacitors in the range of 15,000 to 30,000 mfd. Low level power (usually ±10 V) is obtained on the servo amplifier circuit board through decoupling and zener diode networks. This obviates the need for good regulation in the high current supply.

In some special cases where very high currents are encountered or where a light-weight supply with very poor regulation must be used, it is desirable to use two separate power sources, but normally this is not necessary.

As a general rule, the current requirements are on the order of 5 amps continuous duty with pulse current capabilities of about 10 - 15 amps; most systems fall in this range.

OPERATION AND ANALYSIS

Included in this section is a discussion of some of the more important technical aspects of the S-1 system from the points of view of operation and servo analysis, so as to present a clear picture of the system concepts and techniques employed.

General Operation

Shown in Figure 2 is a block diagram of a complete system which operates as follows: The output from the optical tachometer pre-amplifier is fed to a high gain amplifier-limiter module which generates clipped square waves while preserving the timing integrity (phase) of the solar cell output. This technique insures a minimum of frequency modulation or phase shift in the feedback signal due to possible amplitude modulation in the pick-off signal. The square waves are fed to a regenerative trigger circuit and differentiator so that the resulting signal is a series of sharp-rise-time short duration pulses of about 5 volts amplitude.

The reference frequency source (which should have a square wave output) is similarly fed to a trigger and differentiator, and produces a like series of pulses. The two signals thus formed are then fed to the inputs of the "synchronous acquisition system" which consists solely of digital logic circuits,* whose function it is to make continuous determinations as to whether the motor speed is too slow, too fast, or synchronized with the reference, and further, when in synchronism, to determine the electrical phase angle between the feedback and reference pulses. The use of digital circuits in this manner to lock the system into synchronism and to determine the instantaneous operating conditions has distinct advantages: they preclude the need for frequency selective (tuned) circuits which at best are awkward to handle for multi-speed applications, and they are not sensitive to the problems associated with transistor drift.

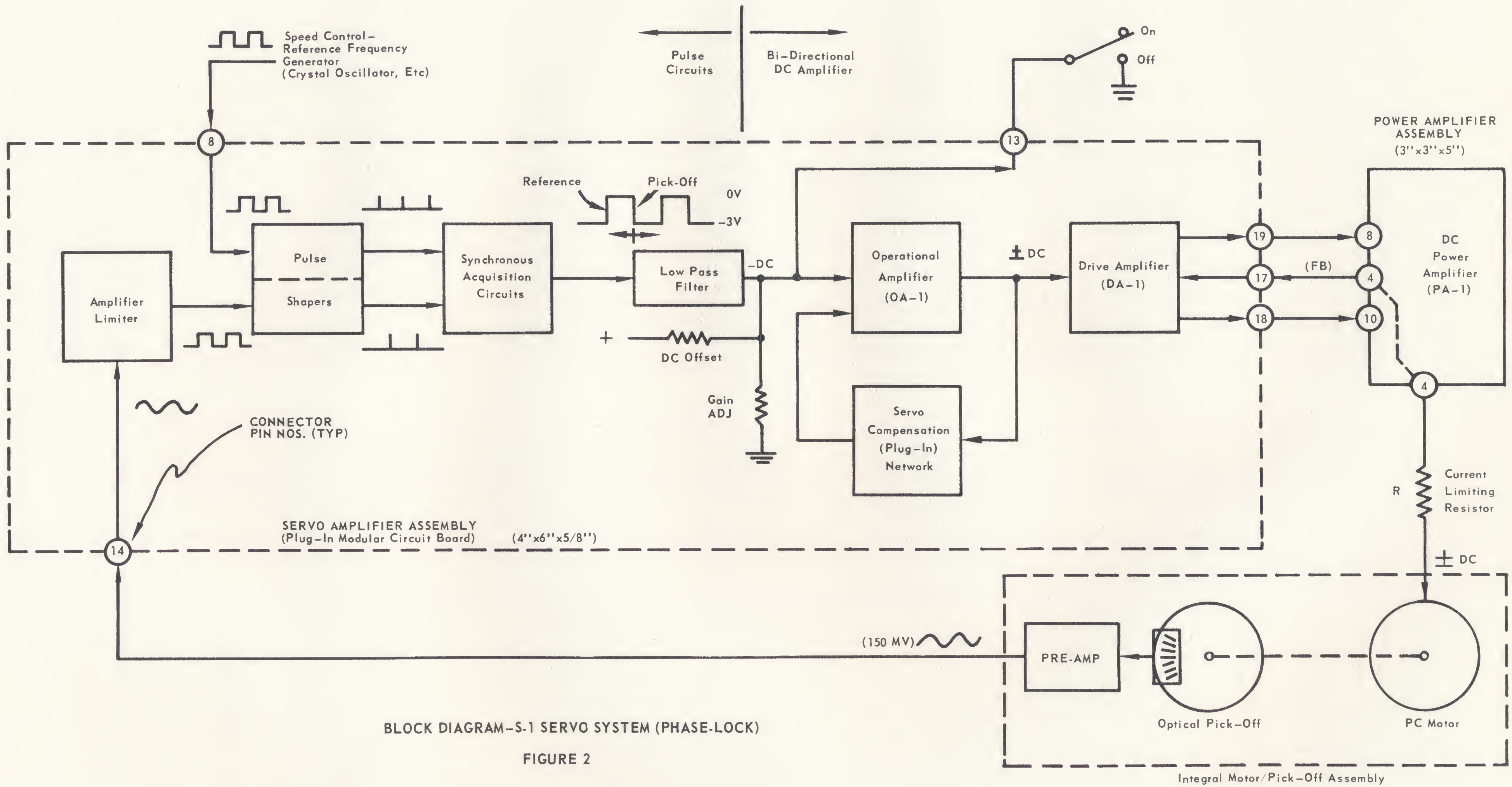
In practice, there are three possible output signals from the logic circuits: the output for the "too slow" condition is 0 volts which will cause the power amplifier to saturate in one direction resulting in maximum motor acceleration; the output for the "too fast" condition is -3 volts which saturates the power amplifier in the other direction and results in maximum motor deceleration; and the third output, signifying synchronous operation, is a 3 volt square wave, the leading edge being generated by the arrival of a reference pulse, and the trailing edge by the arrival of a pick-off pulse; it is, in fact, a flip-flop which is alternately turned on and off by reference and pick-off pulses.

Clearly, variations in the pulse width of the synchronous square wave thus formed are a measure of the phase angle or the "relative position" of the two signals, and therefore represent the instantaneous position of the motor shaft with respect to the reference. In other words, the square wave is width modulated by the instantaneous position "jitter" of the motor shaft. This constitutes the phase comparator referred to earlier.

The transition from one output condition to another is positive and virtually instantaneous, and the logic is arranged so that it is not possible for the motor to "side lock" at some multiple or sub-mutliple of the command speed.

The next step in the operation is to remove the "carrier" or reference frequency from the signal by passing it through a simple low pass filter which leaves an average DC voltage proportional to the pulse width of the square waves.

*Patent applied for



BLOCK DIAGRAM–S-1 SERVO SYSTEM (PHASE-LOCK)

FIGURE 2

From this point on the system is essentially a DC amplifier which requires 0 volts in for 0 volts out, in which case the motor is at rest. There is, of course, a net average current required to drive the motor continuously at some speed, and since our available DC operating signal lies in the range of 0 to -3 volts, (the limits of the square wave), a (+) DC offset voltage is injected into the signal at this point in order to shift the level of the driving voltage by a fixed amount. This offset voltage is adjusted so that the synchronous square wave has approximately a 50% conduction angle when the motor is running under no load conditions at a mid-range speed.

It should be noted that the net DC driving voltage entering the amplifier is the same regardless of the adjustment of the added offset voltage; this is because the self compensating action of the servo loop will automatically reduce the conduction angle if the offset voltage is increased, and vice versa. From another point of view, one might consider that the (+) offset voltage is sufficient by itself to drive the motor at approximately the correct speed, and that the phase comparator signal is superimposed on this voltage to provide the system control function. The choice of a 50% conduction angle is somewhat arbitrary, but insures that there is sufficient room for position deviation either side of "center" to saturate the amplifier for both positive and negative torque loads, before the system drops out of synchronism.

More will be said in later sections about the detailed characteristics of the changes of phase angle or "position" which take place in the presence of various types of torque loads.

The first section of the DC amplifier is a conventional high gain operational amplifier module used in the non-inverting connection. As indicated in the block diagram, there is a feedback loop around this amplifier which contains a plug-in compensation network. This network provides all the frequency selective circuits necessary to stabilize the servo (being a position rather than a velocity servo, stabilizing circuits are required), and establishes the maximum mid-band and DC gain characteristics of the system. Final overall gain is adjusted by means of the shunt resistor at the input to the amplifier. Additional details on the requirements and functions of these circuits will be given in the next two sections.

The remainder of the DC amplifier consists of an amplifier module which is mounted on the servo board, and a power amplifier which is an external assembly mounted on a conventional heat sink. These two units, taken as a whole, have an internal feedback loop which limits the voltage gain to about two; the input is driven single-ended from the low impedance output of the operational amplifer, and the output, operating push-pull class B, is capable of supplying bidirectional currents to the motor up to 8.75 amperes. The current limiting resistor (R) in the block diagram is adjusted to limit the current to this amount so that the power dissipation rating (34 watts at 25° C) of the output amplifier cannot be exceeded under any continuous duty operating conditions. Further information on possible deviations from this system current limitation is contained in this paper and other Photocircuits technical literature.

A convenient means for turning the motor on and off without interrupting system power is provided by a lead which is connected to the input of the operational amplifier and brought out to a terminal on the circuit board connector. Shorting this lead to ground through a toggle switch will hold the amplifier output at 0 volts regardless of the signals coming from the phase comparator and the DC offset voltage, and the motor will coast to a stop.

In order to control the acceleration up to synchronous speed or the deceleration to stop, it is a relatively simple matter to devise various ramp functions through the controlled charging and discharging of a capacitor, and to operate these external circuits in conjunction with the on-off switch.

System Analysis

An analytical discussion of the S-1 system from the servo theory point of view can take many forms; a thorough dissertation would of course include complete transfer function equations and curves to describe all aspects of the servo in detail, however, this kind of treatment is beyond the scope and purpose of this paper. Included, however, are those diagrams, curves, and explanations which are necessary to cover both a general analysis of the servo and a specific design example so that the systems designer may gain a practical insight into the all-important interrelationships between the significant operating parameters.

GENERAL

Although the S-1 Servo may be considered as an extremely precise speed control system, it is more accurate (and convenient) to think in terms of position control since in reality the system is a position control servomechanism and must be analyzed from this viewpoint. Of primary concern is the instantaneous position of the shaft with respect to the instantaneous position of a "perfect" reference which is moving in synchronism with the shaft. For purposes of analysis one may consider the device as a stationary position servomechanism with its operating conditions superimposed upon a constant operating velocity.

This describes a type 1 servo, a class of systems which are inherently unstable due to a built-in 180° phase shift, requiring, therefore, suitable lead-lag phase shift networks in order to achieve stable operation and critical damping, if desired. It is interesting to note that the often troublesome "dead-band" problems normally associated with a stationary position servo are non-existent in this device, because the motor shaft is in constant motion thus requiring a continuous flow of current, even if it is, at times, in a negative direction.

A factor not encountered in a stationary DC position servo, but which can cloud the picture in this device if not taken in its proper perspective, is that it operates as a sampled data system. A most important result of this fact is that the information on position is not continuously available, but is quantized or sampled at a rate determined by the reference frequency, at one sample per cycle of the reference.

A little thought will show that this situation produces some conditions which cannot be overlooked, since they result in the fact that the phase comparator gain has a high frequency transmission characteristic which may have a serious effect upon the performance obtainable from the whole system. For example, if we assume that the phase comparator makes 100 measurements per second then it is apparent that we cannot determine what is happening to the shaft position in an interval shorter than 1/100 second.

An adequate description of the resultant sampling amplitude loss and its associated "transportation delay" can be obtained from the theory of scanning apertures. This analysis, not covered here, shows that the position gain falls to zero transmission at the carrier (reference) frequency, and that the phase shift is lagging and is linearly proportional to the ratio of the signal to the carrier frequency, reaching 180° at the carrier. The obvious implication, then, is that the reference frequency should be kept as far above the servo cut-off frequency as possible so that the sampling effects will be minimized.

In practice, the effect which must be watched is that as the motor speed is reduced by lowering the reference frequency, a point is reached where the proximity of the reference to the servo cut-off frequency will cause increasing phase shift such as to partially negate the effect of the compensating networks,and the servo will eventually become unstable. Remembering, also, the requirement for removing the reference frequency by suitable filtering in order to obtain an average DC control signal, it is evident that this filter, in itself, may also cause phase shift which intrudes upon that required by the compensation networks for system statility.

Since the requirements for phase lead in the compensation networks and the phase lag produced by filtering and reference frequency phenomena are mutually conflicting, a situation is encountered which dictates, as a rule of thumb, that the reference frequency must be at least five times removed from the upper frequency limit or the "cross-over point" of the servo.

This is a vitally important consideration in the design of a practical system, and imposes the basic minimum speed limitation for a given set of conditions. In order to further reduce the motor speed one of two things must be done: either the servo bandwidth must be reduced or the nominal reference frequency requirement must be raised by increasing the bit density of the motor pick-off device. The servo bandwidth may be reduced either by reducing the loop gain of the system or by adding mechanical inertia. More specific design information on this subject will be given subsequently.

A SAMPLE ANALYSIS

The design analysis example which follows is based on a standard low inertia system of the type shown in the specification literature on Standard S-1 Servo Systems, and is typical of a device which might be used as a capstan drive for a magnetic tape transport.

The most direct approach to understanding the phase locked system is to construct a block diagram of the servo loop and to analyze briefly its behavior by the methods which are commonly used in considering feedback systems. This diagram is shown in Figure 3.

The operator s is the conventional one used in systems analysis. It may be replaced with the variable $j\omega$ and has the dimensions of frequency. Where we are interested in velocity as an output from the shaft, we can obtain an answer by simply passing the shaft position through a transfer function having a value s. This is physically equivalent to noting that velocity is the derivative of position or that a system which displays a flat position response will display a velocity response which rises at a rate of 20 db per decade with frequency. Thus the operator s, used throughout the analsis, simply inserts a 20 db per decade rise in this context.

The G terms in the diagram denote the transfer function gains for the various elements which make up the loop, as developed in the text. The mechanism for considering the position or velocity disturbances caused by torque loading is shown by the torque input point T_L.

It will be noted throughout that position, velocity and voltage gains have been converted to db. This is purely a convenience, and simply means in Figure 10, for example, that the position response (from point f_1 to point f_2) resulting from a one oz-in torque load will be "down" 94 db. In other words, each oz-in of torque loading will cause a position change of -94 db or 0.00002 radians.

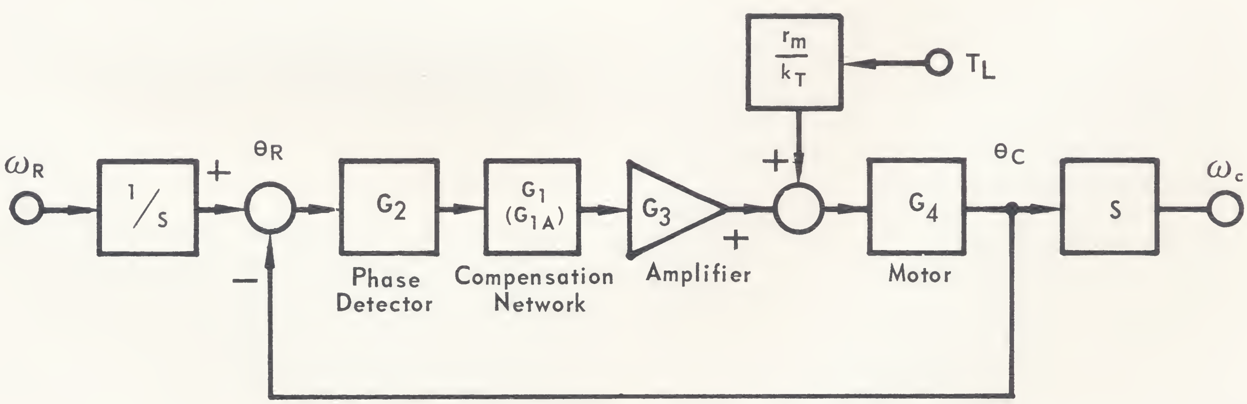


FIG. 3 –Complete Servomechanism Network

SYSTEM PARAMETERS

Motor/Tach = D 1523 (368 motor with optical tach)

Motor Inertia = .004 oz-in-sec^2

Load Inertia = .0006 oz-in-sec^2 (opt. pick-off)

Total Inertia = .0046 oz-in-sec^2

Motor k_e (back EMF) = 2.22 volts per 1000 rpm

= .021 volts per radian per second

Motor R_m (regulation) = 66.7 rpm per oz-in loading

= 7 radians per second per oz-in

Motor and Load Time Constant, $T_M = R_m$ x Inertia

= 7 x .0046 = .032 seconds

Break Frequency,

$$f_1 = \frac{1}{T_M} = \frac{1}{.032}$$

= 31.3 radians per second

= 5 cycles per second

The frequency response of the motor as a velocity transducer is given by

$$G\omega = \frac{1}{k_e\ (1 + T_M s)} = \frac{1}{.021\ (1 + .032s)}$$

$$= \frac{47.5}{(1 + .032s)} \quad \text{radians per second per volt}$$

This is plotted in Figure 4.

(at DC, gain G_ω = 47.5 radians per second per volt, or 33.5 db).

The position transfer function G_4 is

$$G_4 = \frac{1}{k_e\ s\ (1 + T_M s)} = \frac{1}{.021\ s\ (1 + .032s)}$$

$$= \frac{47.5}{s\ (1 + .032s)} = \text{radians per volt}$$

Also plotted in Figure 4.

(Note that at DC, position gain G_4 is infinite, therefore low frequency gain is considered at 1 radian per sec (0.16 cps) where s = 1).

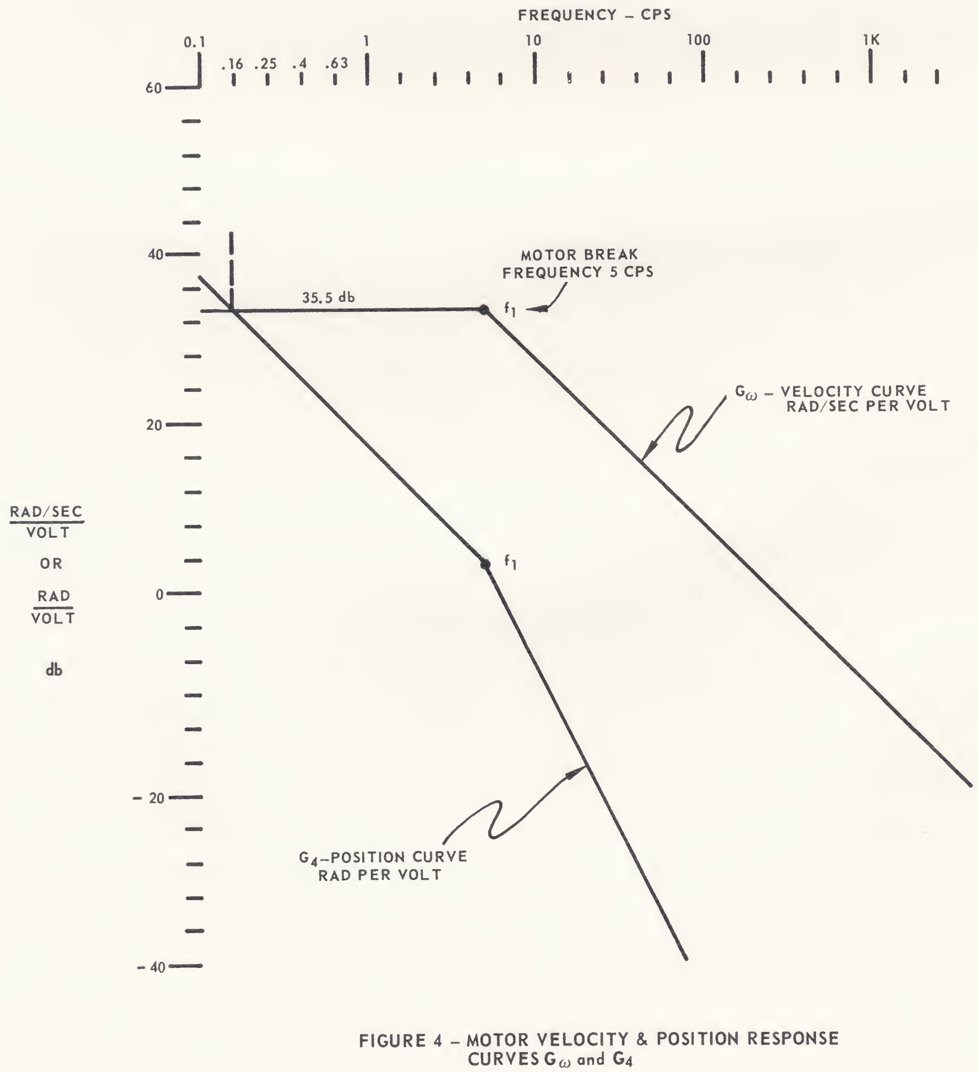


FIGURE 4 – MOTOR VELOCITY & POSITION RESPONSE CURVES G_ω and G_4

The servo amplifier component is assumed to have no frequency response limitations in relation to the rest of the system, thus

$G_3 = 31.5$ volts per volt (30 db)

Plotted in Figure 5.

The phase comparator gain is associated with the forward gain in the transfer function G_2. It is derived from the 3 volt swing for 360 electrical degrees of phase motion, and assumes a pick-off pulse density of 5000 pulses per revolution. Also included in G_2 is the effect of the final overall system gain adjustment network referred to earlier and shown in the block diagram of Figure 2. For our example, the phase comparator gain is reduced by a factor of about 9 by this adjustment. Attention is drawn again to the previous comments concerning the effects of a sampled data system at high disturbing frequencies. At very low frequencies (or DC), however, consistent with these remarks, the situation is analogous to that where position information is obtained from a DC potentiometer, thus G2 has the dimensions of volts per radian displacement of the motor shaft.

$$G_2 = \frac{3}{2\pi} \times 5000 \times \frac{1}{9} = 267 \text{ volts per radian}$$

Combining these functions we may now determine the overall system open loop position gain,

$$\begin{aligned} G_4 \cdot G_3 \cdot G_2 &= 47.5 \times 31.5 \times 267 \\ &= 400{,}000 \\ &= 112 \text{ db} \end{aligned}$$

This composite curve is plotted in Figure 6.

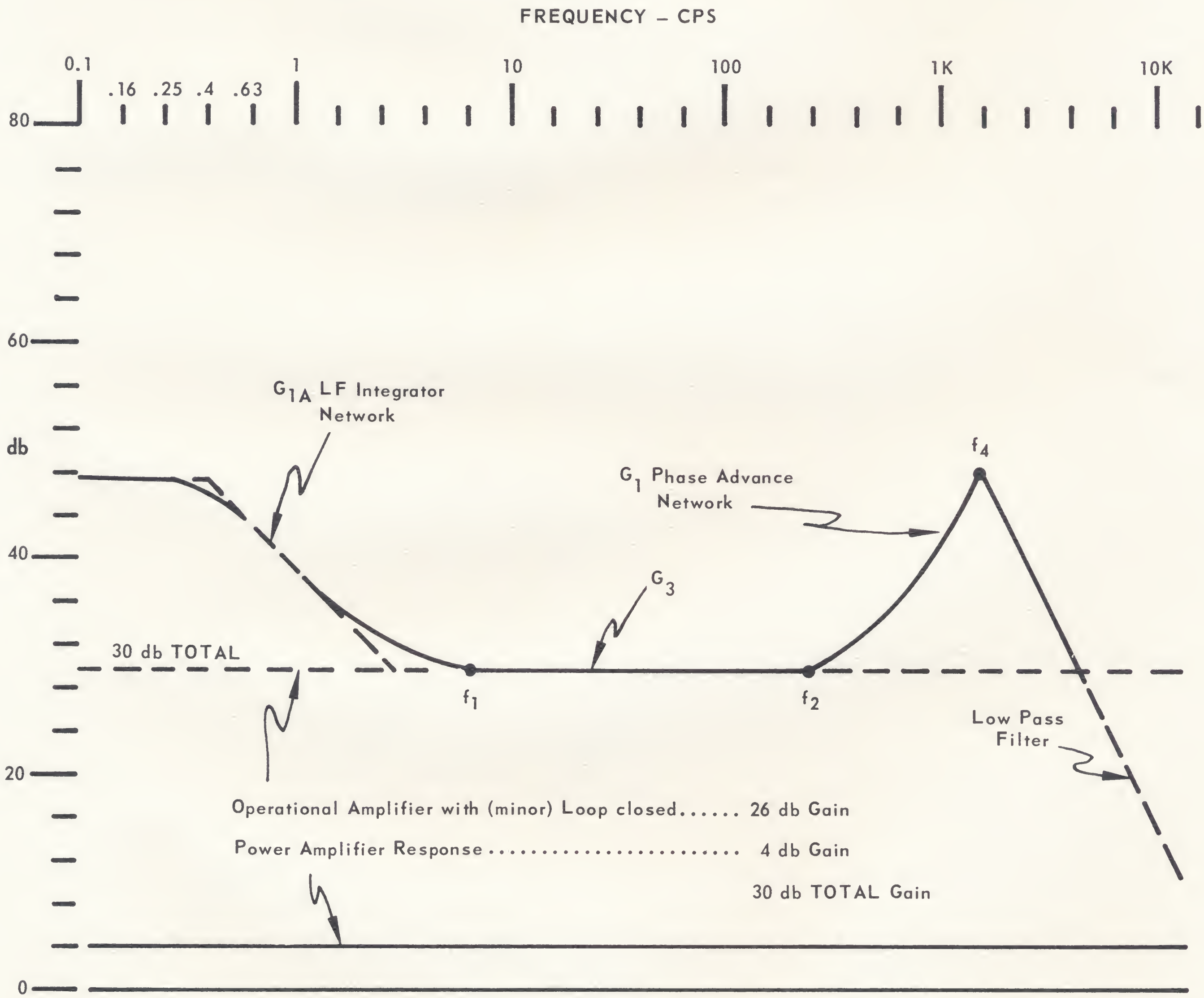


FIGURE 5 – DC AMPLIFIER RESPONSE CURVES

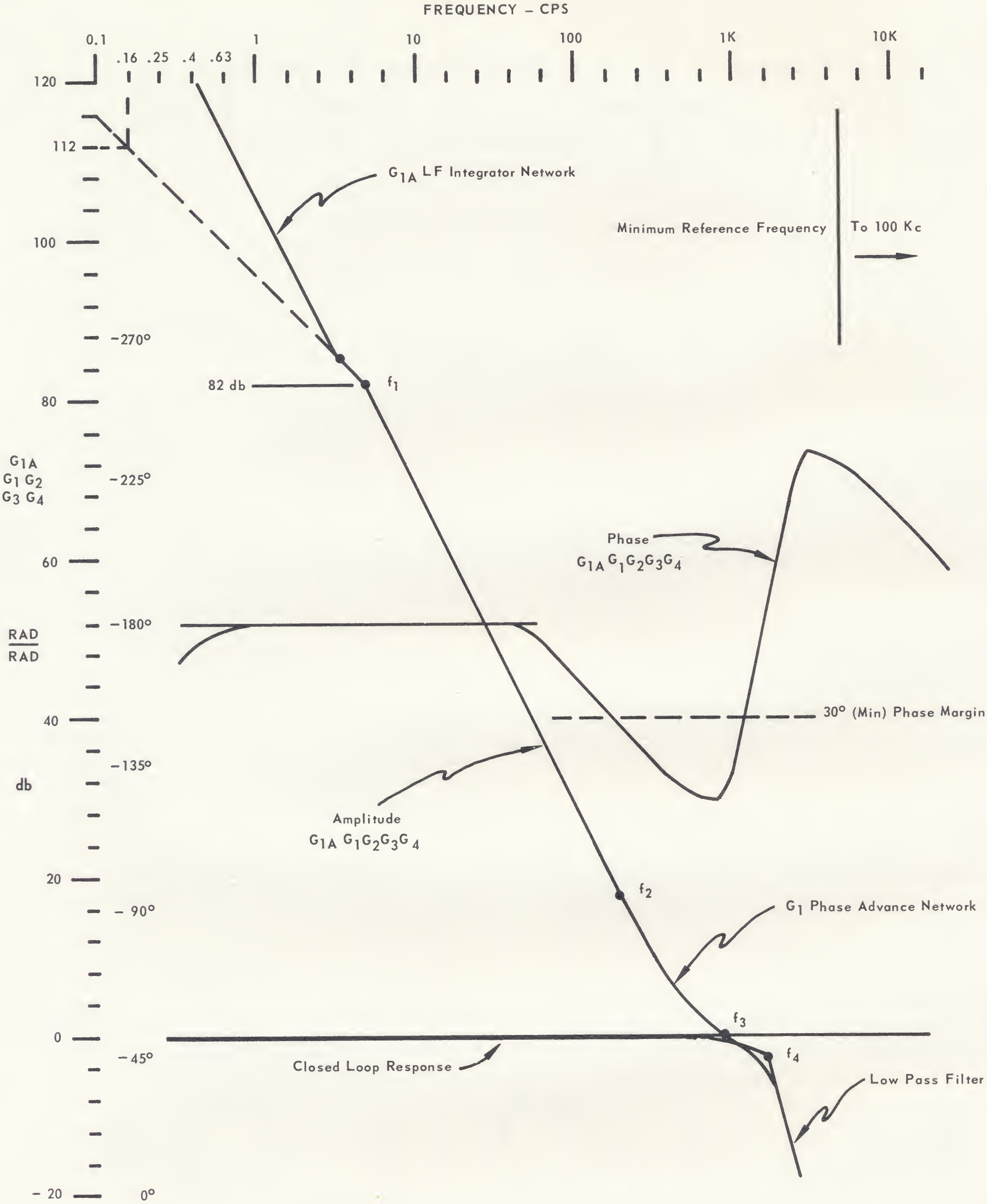
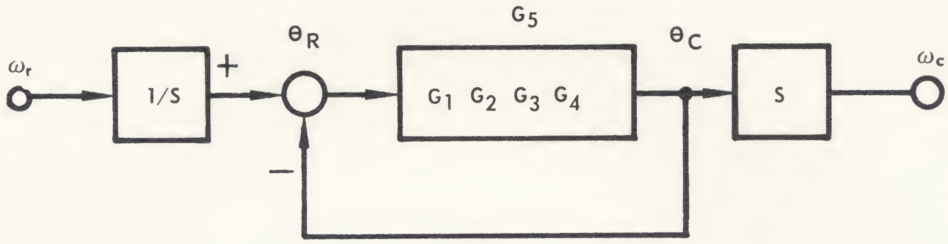


FIGURE 6 – SYSTEM OPEN LOOP POSITION CURVES

G_1 curve shown in Fig. 5 and Fig. 6 is the phase advance network required for system stabilization and has no effect at low frequencies. G_{1A} curve (Fig. 5 and Fig. 6) is the low frequency integrator network used in most systems to provide about 18 db additional gain at DC. (This helps maintain a 50% conduction angle in the phase comparator at any speed in the presence of any practical steady state torque load). For simplicity, its effect is not included in the above gain calculations, but is shown in all applicable curves.

When the loop is closed, the unity gain crossover point will define the small signal frequency response of the system as shown in Figure 6, and by the relationship in the block diagram of Figure 7. Here, the transmission characteristic is from position to position (or velocity to velocity) and is flat up to the crossover point. The response when a torque load is injected into the loop equation is covered in the next section.



$$\frac{\omega_c}{\omega_r} = \frac{\theta_c}{\theta_r} = \frac{S}{S} \cdot \frac{G_5}{1+G_5} \cdot$$ radians per radian or rad/sec per rad/sec

FIG. 7 Network for forward Transmission and Frequency Response Determination

SYSTEM PERFORMANCE

Performance characteristics can best be examined by constructing system position and velocity response-to-torque-loading curves under closed loop conditions.

Application of disburbing torques to the motor shaft results in a deviation of shaft position (or velocity if we multiply by transfer function s) according to the system shown in the block diagram of Figure 8. To construct the curves, the first step is to modify the motor position function, G_4, from radians per volt to radians per oz-in torque loading by introducing the dimension factor r_m/k_T.

Calling this new function G_4T, we have

$$G_4T = \frac{r_m}{k_T} \cdot G_4 = \frac{0.5}{3} \cdot \frac{47.5}{s\ (1 + .032s)}$$

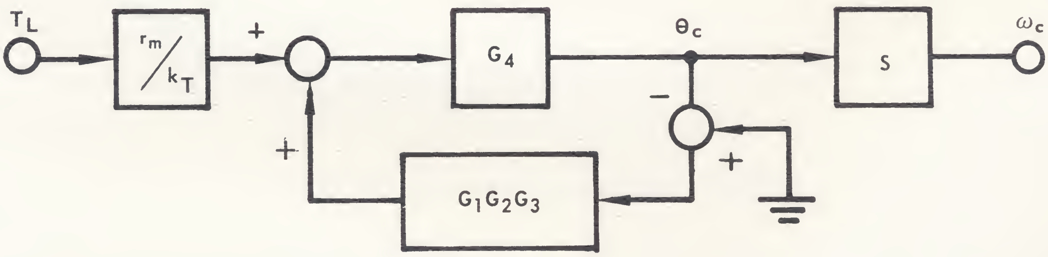
$$G_{4T} = \frac{7.9}{s\ (1 + .32s)}$$ radians per oz-in

where motor DC resistance $r_m = 0.5$ ohms, and torque per ampere $k_T = 3$ oz.-in per ampere. Converting the numerator of G_{4T} to db (7.9 = 18 db) we may plot the motor (only) position response to torque loading in radians per oz-in. This curve is shown in Figure 9.

These functions may be seen in Fig. 8 where G4 is shown as the forward element modified by r_m/k_T in the closed loop equation.

We may now conveniently calculate the system position response to torque loading as shown in Figure 10 by taking data directly from Fig. 9 (G_{4T}) and Fig. 6 (G_1, G_2, G_3, G4) and performing the operations indicated in the equation of Figure 8. Ignoring for the moment the effect of the G_{1A} Integrator Network, most of the work can be done by inspection by noting that the shape of the two curves is identical down to the point f_2 on Fig. 6. The gain difference as measured at the corner frequency f_1 is (-12 db -82 db) or -94 db; thus the position response is flat at -94 db to point f_2 or about 250 cps. Above f_2 the two curves are falling at different rates, and at approximately f_4 the system reverts to a 40 db per decade slope - the slope of the motor response curve itself. The net result, including the effect of G_{1A}, is shown in the diagram of Figure 10. It is interesting to note, though not unexpected, that the shape of the position curve of Figure 10 is the inverse of that of the electronic amplifier of Fig. 5 up to about point f_4.

Conversion to a curve showing system velocity response to torque loading is accomplished (in accordance with the loop equation of Fig. 8) through multiplication by s, which inserts a 20 db per decade rise on the position curve. This is shown in Figure 11. The approximate "maximum value" of the mechanical velocity impedance curve (portion f_2 - f_4 on curve of Fig. 11) may be calculated directly from the following relationship derived from the loop equation of Figure8).



$$\frac{\omega_c}{T_L} = S \cdot \frac{r_m}{k_T} \cdot \frac{G_4}{1+G_1G_2G_3G_4} \cdot$$ radians per second per oz-in loading

FIG. 8 – Network for Determing Response of Shaft to Load Torque Disturbance

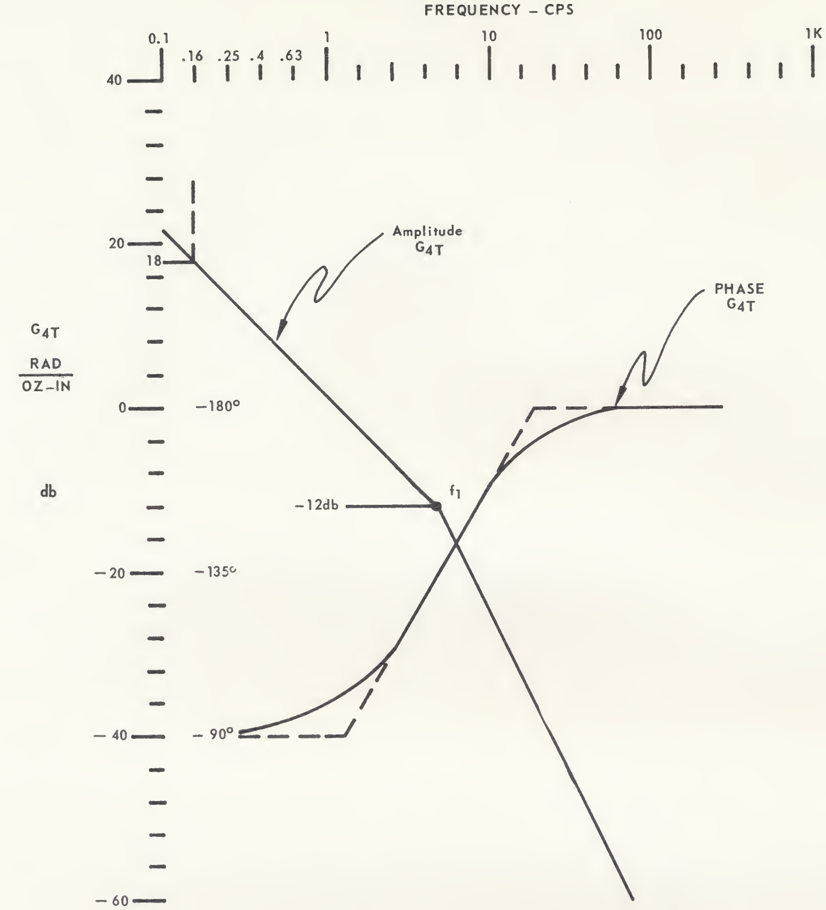


FIGURE 9 – G_{4T}, MOTOR POSITION RESPONSE TO TORQUE LOADING–RADIANS PER OZ–IN

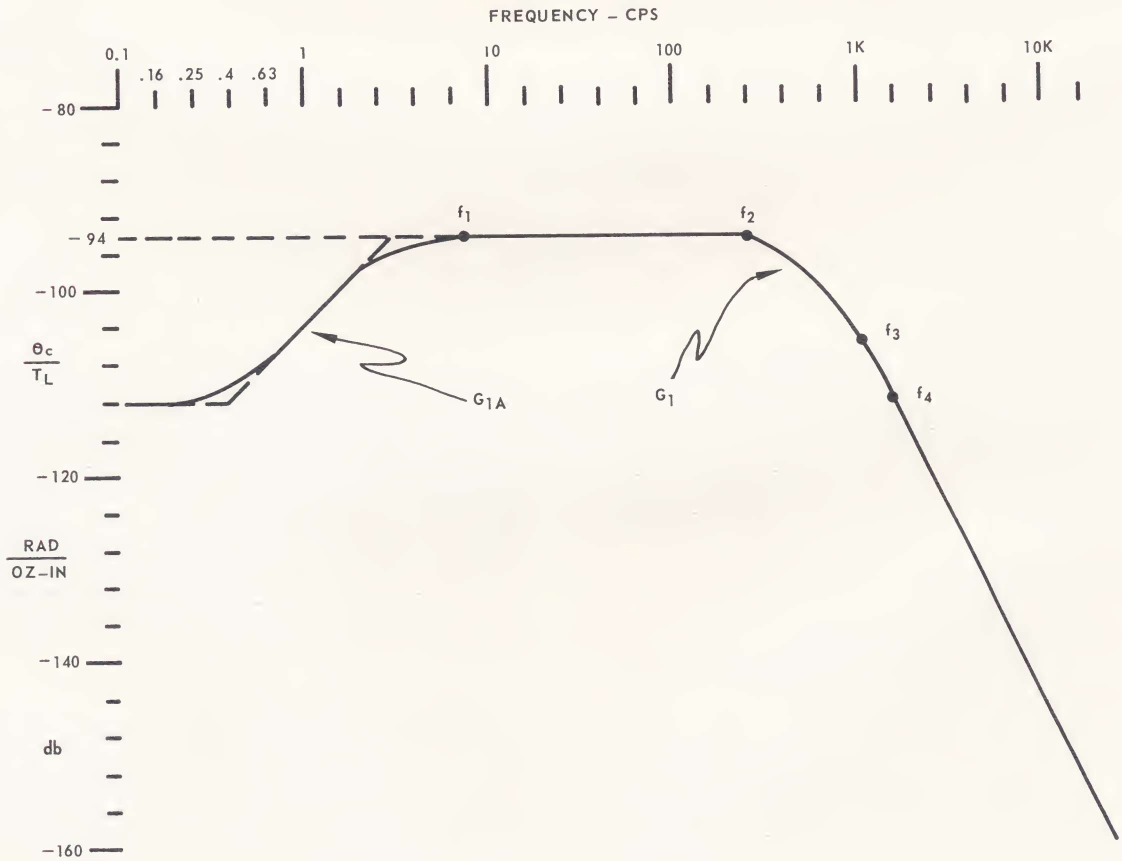


FIGURE 10 – $\frac{\theta_c}{T_L}$, SYSTEM POSITION RESPONSE TO TORQUE LOADING RADIANS PER OZ–IN

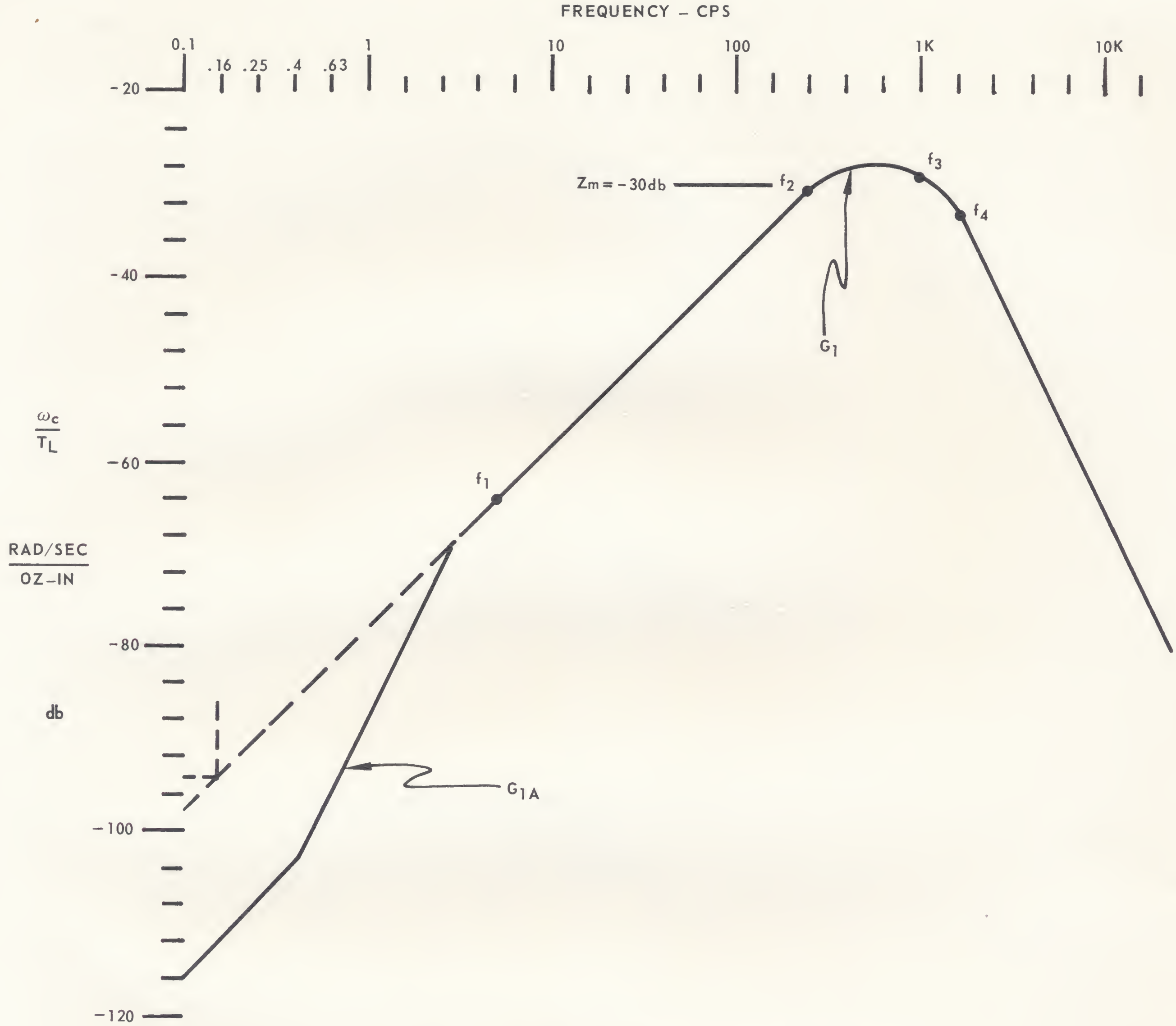


FIGURE 11 – $\frac{\omega_c}{T_L}$, SYSTEM VELOCITY RESPONSE TO TORQUE LOADING RADIANS PER SEC PER OZ-IN

Maximum mechanical velocity impedance,

$$Z_M = s \cdot \frac{G_{4T}}{G_1\ G_2\ G_3\ G_4} \text{ rad/sec per oz-in}$$

with s set equal to $j\omega$ at the frequency f_2 where G_1 phase advance compensation begins. This is equivalent to

$Z_M(\text{db}) = s\ (\text{db}) + G_{4T}\ (\text{db}) - G_1\ G_2\ G_3\ G_4\ (\text{db})$
$Z_M = 64 + 18 - 112$
$Z_M = 30$ db (Fig. 11) rad/sec per oz-in
(where s at 250 cps = 1570 radian frequency = 64 db).

SIGNIFICANCE OF CURVES

Although the above data gives an approximate analysis for a particular system, the following comments will show that the curves may be easily modified so as to illustrate quite closely the characteristics of most any S-1 System using the printed motor.

There are three basic factors which greatly simplify this process. They are (1) that the mechanical time constants remain fairly close for the different size motors generally used with the S-1 System; (2), the DC voltage amplifier gain G_3 is always kept constant; and (3), the overall phase-comparator gain G_2 is set to be nominally the same for each system. For example, if the 2000 line track on the pick-off is used instead of the 5000 line track, the system gain is increased 2 1/2 times, or 8 db, by changing the value of the gain adjust resistor accordingly.

For low inertia systems, then, the motor break point, f_1, will always be at about 5 cps as shown in Fig. 4. The location of the curve vertically, in other words the motor position gain, G_4, is set as per the sample analysis by using the appropriate motor back EMF data from the motor specification sheet. ($G_4 = \frac{1}{k_e}$ where S=1).

G_3 is constant, so Fig. 5 applies as is for low inertia systems. A new curve for Fig. 6 may now be constructed; its slope remains the same, but it is moved up or down vertically by the amount that the curve of Fig. 4 has moved. Thus the curves of Fig. 4 and Fig. 6 for the 488 motor, for example, would both be shifted down about 6 db indicating that the system open loop position gain is reduced by 6 db. This illustrates only that the motor voltage sensitivity is reduced as the motor size in increased which is to be expected.

If we proceed now to construct a new curve for G_{4T} we find from the example, since $G_{4T} = \frac{r_m}{k_T} \times G_4$ we have for the 488 motor a 12 db improvement in the motor position response to torque-loading. While we had a reduction in voltage sensitivity for G_4 by a factor of 2, we now have an increase in "position correction" sensitivity by a factor of 4. The fundamental reason for this apparent anomaly is that the voltage sensitivity is a function only of k_e, while the position sensitivity, or in effect the slope of the speed-torque curve, is a function of both k_e and k_T and thus the "regulation" is improved by a factor of 4 in this case.

Combining Fig. 6 and Fig. 9 in order to derive our new final closed loop position curve for the 488 motor, we find a net system improvement of 6 db, since the open loop gain of Fig. 6 has been reduced by 6 db and the position sensitivity of Fig. 9 has been increased by 12 db.

If we consider the fact that the k_e and k_T change is roughly the same proportion for motors normally encountered with the S-1 system, we arrive at the interesting final conclusion that the overall system response to torque loading improves in proportion to the change in motor torque per ampere, k_T, other parameters being equal.

The two remaining factors requiring clarification are the effects of adding an external inertial load, and the requirements for phase compensation. The latter subject will be covered in the next section.

The primary effect of adding inertia to the system is that the motor/load break frequency, f_1, will of course shift downward in frequency. Since system gains remain essentially the same, the servo bandwidth will be proportionally reduced, which in turn requires that the phase shift networks be moved down in frequency by a like amount in order to retain system stability. An important side effect, referred to earlier, is that the minimum "safe" reference frequency may now also be moved proportionally downward resulting in lower practical system speeds.

It should be pointed out that for constant speed systems this reduced bandwidth does not degrade the performance of the servo since we are in effect trading control bandwidth for an increased mechanical filtering or "smoothing" effect by virtue of the added inertia. Systems, however, which are designed to "follow" a constantly changing reference frequency, such as those sometimes found in magnetic tape devices which are required to "servo off the tape", inherently require low inertia wide bandwidth characteristics and preclude extremely low speed operation.

High speed operation is not affected by the addition of external inertial loads unless mechanical imbalance generates equivalent torque loads which are outside the power handling capabilities of the system.

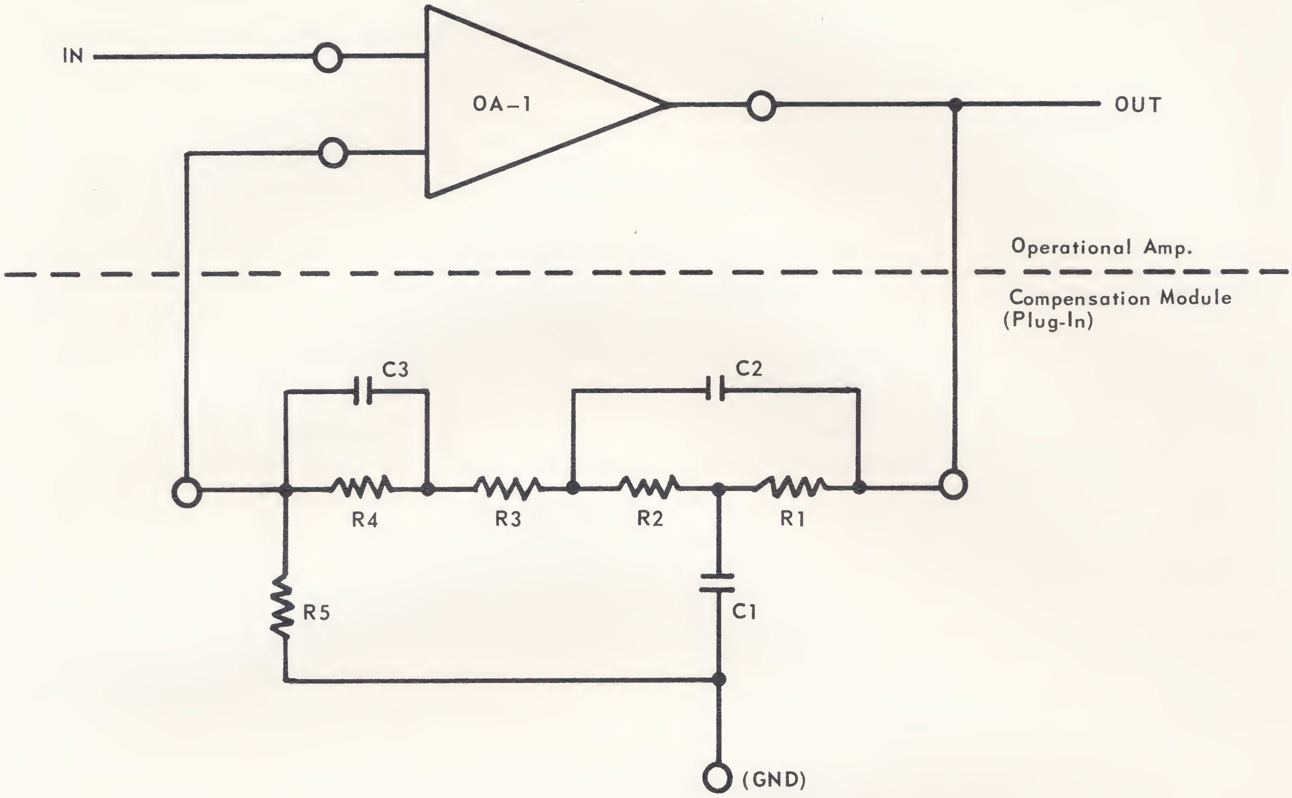
In order to generate a new set of approximate curves for a system with added external inertia, it is only necessary to calculate the new break frequency, f_1, use the methods described to determine servo gains, and proceed as shown in the sample analysis. Having done this, incidentally, the approximate low speed limitation may be readily determined by recalling that the minimum practical reference frequency should be (at least) 5 times higher than the system bandwidth as explained earlier in this section. A general curve showing the relationship of minimum speed versus inertia appears later in this paper.

Compensation Networks

The problem of phase compensation in the S-1 servo, already referred to in earlier sections, is one which requires particular attention for each system design. The open loop curve of Fig. 6 shows that the servo gain is falling off at the rate of 40 db per decade beyond f_1, the motor break frequency, which is typical of position systems with one break point. As is the case in any feedback system, this degree of attenuation will cause 180° phase shift and, if allowed to continue at this rate across the unity gain line, the system will be unstable and therefore oscillatory. The theory behind this phenomenon will not be considered here, but can be analyzed in detail by means of Bode plots or the well-known Nyquist criterion of stability.

The solution to the problem in this case is to use frequency selective networks in the amplifier feedback path so as to "unwind" the phase shift such that the slope across the unity gain line more nearly approaches 20 db per decade. The degree of slope at this point will determine the phase margin and thus the amount of peaking at the high end of the response curve. The final detailed characteristics of these networks are somewhat dependent upon the application, and other system parameters such as speed range and inertia, but the design of an approximate network is generally a straightforward matter.

Fig. 12 shows a schematic drawing of the basic circuits used, and when broken down can be seen to contain a bridged-T filter, an isolation resistor, and a low frequency integrator circuit. The bridged-T filter, being placed in the feedback path, produces an inverted notch with characteristics approximately as shown in the upper frequency portion of the amplifier curve designated G_1 in Fig. 5. Its effect in the vicinity of unity gain can be seen in Fig. 6, where the slope is considerably flattened out. This network actually serves two purposes: it provides the required phase lead, and also provides a fairly sharp cut-off at frequencies above the notch in such a way as not to negate the phase lead effect. In practice, this cut-off slope and the similar curve generated by the reference frequency low pass filter are mutually adjusted so that in effect the low pass filter takes over where the notch filter leaves off, namely, at the nominal gain level (30 db, curve G_3) of the DC amplifier. This composite curve assures that the system gain is cut off at as low a frequency as possible, resulting in optimum system noise conditions, and allowing the lowest possible reference frequency for minimum speed operation.



Values of R Fixed for all Systems	Values of C for sample Analysis System only
R1,2 – 4.7K	C1 – .0022 MFD
R3 – 10K	C2 – 0.1 MFD
R4 – 100K	C3 – 3.3 MFD
R5 – 1K	

FIGURE 12 – COMPENSATION NETWORK

The usual check-out procedure is to assign a set of component values to the notch filter so that the notch frequency falls an octave or two above the servo cut-off frequency, and then to run the system over its operating range while making empirical trimming adjustments to the network for optimum conditions in accordance with system specifications.

Implicit in the above information is the important fact that one cannot make large inertial load changes to the system without modifying the compensation characteristics accordingly. If necessary, this could of course be handled by simple switching. In any case, it is this network which establishes the final servo stability and damping characteristics when the motor shaft is subjected to external torque loads.

The effect of the low frequency integrator circuit (curve G_{1A}, Fig. 5 and Fig. 6) has been mentioned previously. It is adjusted to "break in" at very low frequencies primarily for the prupose of picking up an extra 18 db or so gain at DC in order to reduce the position shift caused by large steady state torque loads. Since it is effective only at very low frequencies - usually below the motor break point - it does not introduce phase shift or other undesirable effects which in any way compromise the stability of the servo. It may be argued, however, that there is an effect superimposed on the normal damping characteristics of the system, if one considers the (relatively) long term low frequency phenomenon which occurs in the presence of step-type steady state torque load changes. This can best be seen by referring to Fig. 13 which shows shaft position changes for these step loads with and without the integrator network. In practice, virtually the only systems which do not use this extra low frequency gain are those with very large inertial loads where the frequencies involved are so low that the time to charge the integrating capacitor seems inordinately long, causing "soggy" low frequency recovery.

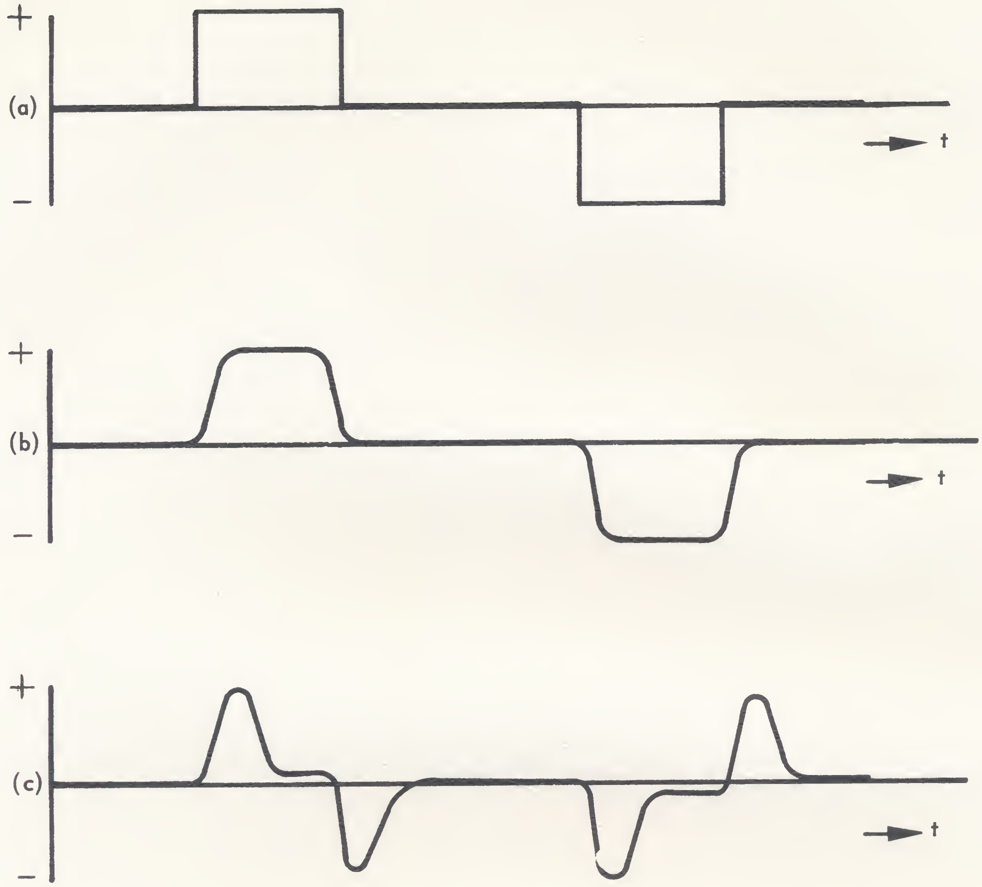


FIGURE 13– DISPLACEMENT AS A FUNCTION OF TIME FOR APPLIED STEPS OF TORQUE; (a) APPLIED TORQUE (b) DISPLACEMENT WITHOUT INTEGRATOR AND (c) DISPLACEMENT WITH INTEGRATOR

In summing up the subject of compensation it should be pointed out that component tolerances are not particularly critical for these networks, and there is fortunately quite a wide latitude possible for both compensation and overall system gain adjustments for a particular system. Thus, a considerable range of operating conditions can be adequately handled with a minimum of new engineering work.

SYSTEM LIMITATIONS

The following three sections are intended to shed additional light on some of the fundamental limitations of the S-1 servo and their interrelationships, so that feasibility studies covering a wide territory may be conducted with comparative ease.

Bandwidth

The fundamental variables which determine servo bandwidth in the S-1 System are: size of motor used, total system inertia, and servo loop gain. Systems which do not have external inertial loads are capable of very wide bandwidths approaching 1 KC, as in the sample analysis system described earlier. As inertia is added to a system, the other two variables being equal, the bandwidth will decrease in a linear manner, and, for a particular design, a new curve showing the unity gain crossover point may be constructed as described for Fig. 6. It is important to note that in the sample analysis the motor position gain (G_4) is established (for convenience) at a frequency of 1 radian per second (0.16 cps) where the operator $S = 1$, and that this point falls below the motor break frequency, f_1, (5 cps). In constructing a new curve for Fig. 6, if the inertia is such that the break point falls below 0.16 cps, the gain location point should be shifted downward to where $S = 0.1$ or 0.01, etc. (0.016 or 0.0016 cps, etc.) so that this point is always below the break point, where the slope is 20 db per decade. When this is done, 20 db should be added to the loop gain figure for each decade that the location point is shifted down, due to the presence of the 20 db slope.

As an additional aid, Fig. 14 shows a plot of bandwidth versus inertia for motors generally used with the S-1 Servo. These are the nominal bandwidths which may be expected, and are based on the standard design center gains used in the sample system.

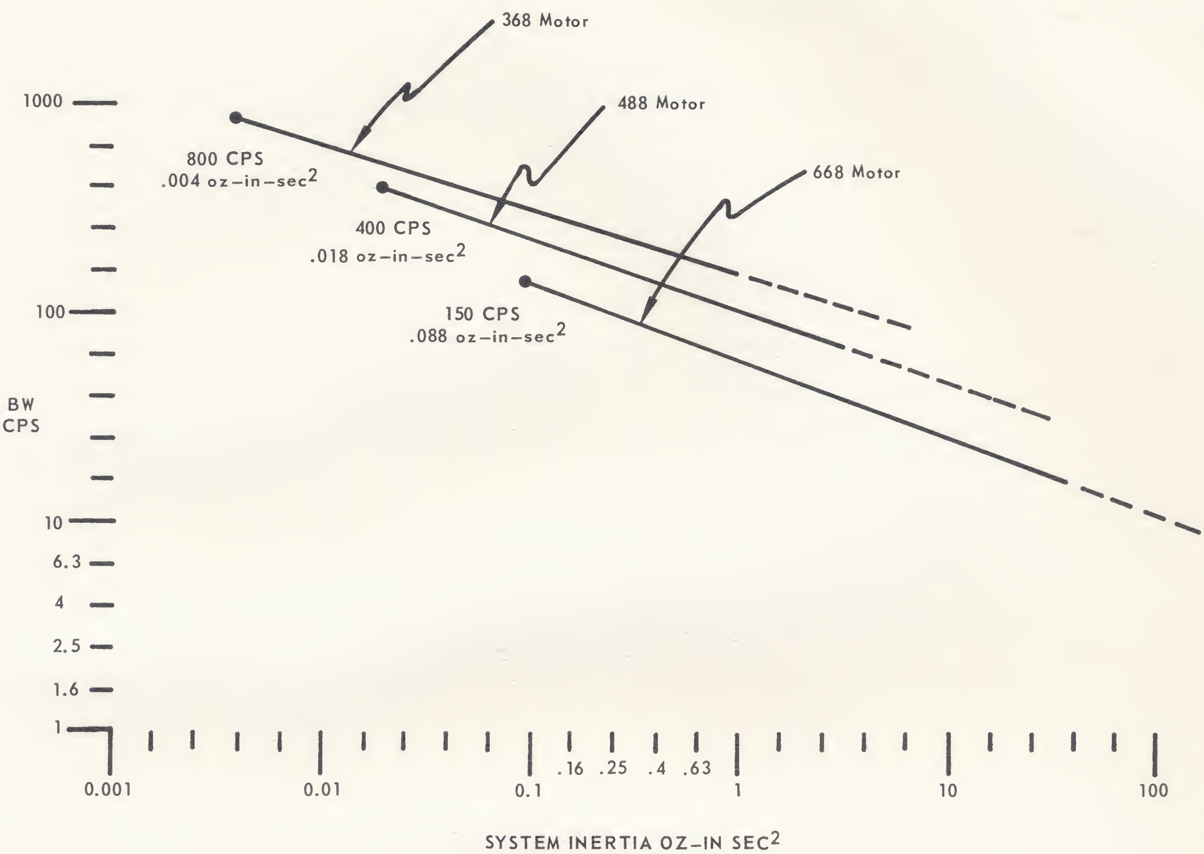


FIGURE 14-APPROXIMATE SERVO BANDWIDTH VS INERTIA FOR REPRESENTATIVE STANDARD MOTORS

Speed Range

The factors which limit high speed operation of the S-1 system are: motor ratings, reference frequency limitation, and motor back EMF at the required speed. The motor data sheets show the maximum rated RPM of each motor. The high frequency limitation of the reference signal is 100 KC which allows adequate switching time for the transistors in the digital circuits; this, of course, sets a top speed which is dependent upon the pulse density of the pick-off. Regarding back EMF, it is important to realize that the voltage generated by the motor subtracts from the voltage available from the power supply (nominally 15 volts), and thus care must be taken to see that at the required speed there will be enough power left in the system to control the shaft in the presence of normal operating torque loads. What constitutes "enough power" is dependent upon the particular system load requirements, but in general there should be at least 5 volts available to operate the servo, indicating a maximum allowable back EMF of about 10 volts.

The factors which control low speed operation, referred to in earlier sections, are not quite so straightforward. Recalling once again the basic requirement to keep the reference signal frequency at least 5 times removed from the servo bandwidth, and the effects of added inertia and system gain on bandwidth, it can be seen that a certain amount of juggling of these parameters is possible in order to achieve a very low speed system. In addition, the speed-reference frequency relationship indicates that the maximum pulse density track (5000 lines) on the optical pick-off disc should be used where low speeds are required.

To restate, then, we can say that low speed operation requires a low reference frequency, reduced bandwidth (by adding inertia), and high pick-off pulse density. In some special cases it is helpful to lower the system gain somewhat in order to further reduce the bandwidth. Note, however, that this also degrades the servo stiffness by the amount of the gain change, which is sometimes an undesirable situation.

The curves of Figure 15 have been prepared to give an approximate idea of the minimum speeds which can be expected for various motors used with a range of practical system inertial loads. Normal servo gains are used to derive this data.

A side effect worthy of mention is a torsional resonance problem which crops up occasionally. This can occur under a set of low speed conditions where the reference frequency falls in the range of the natural mechanical resonant frequency of the particular motor-load combination if the "Q" of the resonance is high enough. The use of large diameter shafts in current devices generally precludes serious effects from this cause although the resonance is still present. A thorough coverage of this problem in general is available in a separate Photocircuits Engineering Memorandum, EM-36.

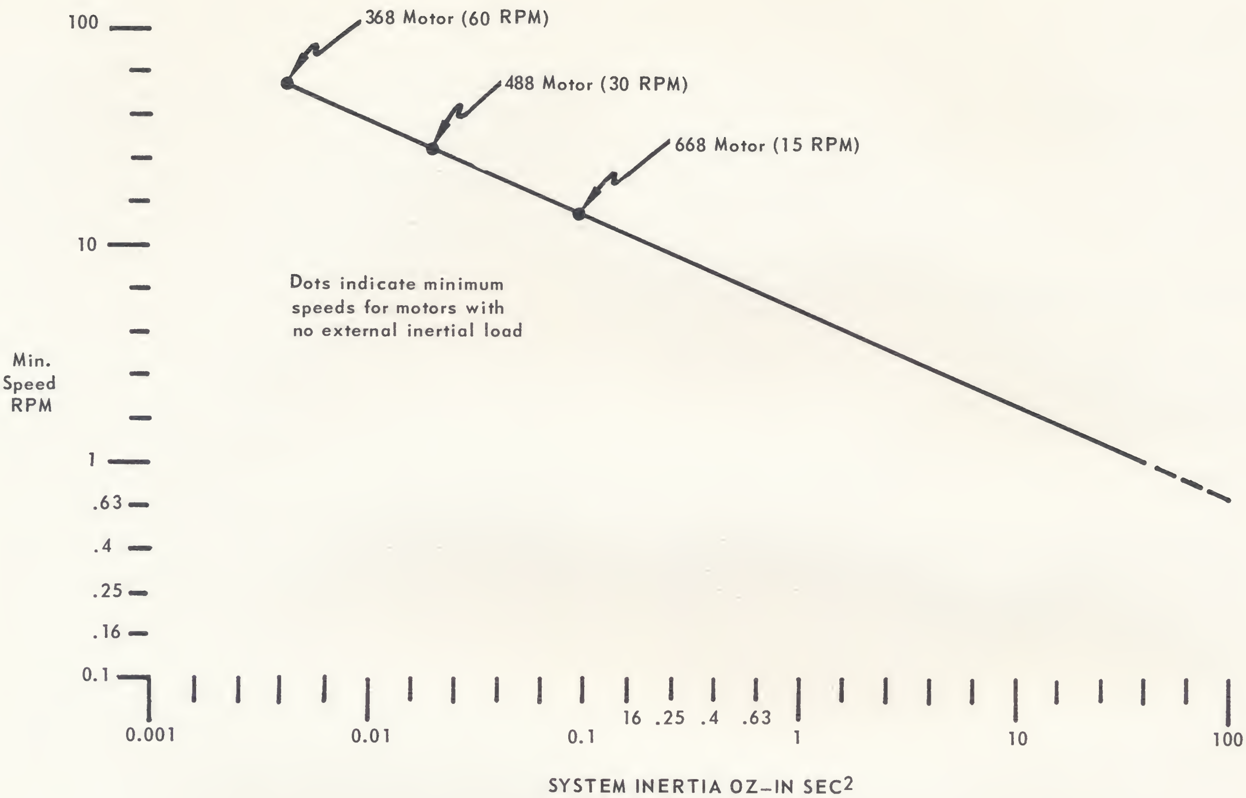


FIGURE 15 – MINIMUM SYNCHRONOUS SPEED VS SYSTEM INERTIA FOR REPRESENTATIVE MOTORS USING NORMAL HIGH LOOP GAINS

Torque - Acceleration

The basic element which generally limits the available torque from a particular S-1 system is the saturation current which can be drawn from the power amplifier. This, in turn, is a function of the voltage and regulation of the power supply and must, at higher speeds, include the voltage cancellation effect caused by the generated back EMF from the motor as discussed in the previous section.

A convenient way to determine the magnitude of available torques under various conditions is to consider the fact that synchronous operation in the presence of increasing torque loads is maintained, by definition, as long as the amplifier is operating in a linear region, which includes all currents up to the point at which the power amplifier saturates. In theory, one could say that the maximum available synchronous torque and the maximum available non-synchronous (acceleration) torque occur at one and the same point, namely, at the amplifier saturation current. Since this current is known or can be determined, it is a simple matter to obtain torque capabilities from the torque per ampere characteristic of the particular motor being considered.

In practice, of course, some reasonable margin of safety, say 10 or 20% for example, should be allowed in making a synchronous torque capability determination. By approaching the subject from this point of view, one is also able to make predictions as to the non-synchronous acceleration rate, and the maximum practical synchronous tracking rate, which is defined as the maximum (ramp) rate that the speed can be changed (by a continuous change in the reference frequency) without allowing the system to drop out of synchronism. Once again, for high speed operation it is important not to overlook the effect of the motor back EMF when making these calculations.

In previous sections we have indicated that a typical S-1 system will employ a ±15 volt power supply and a power amplifier which is current limited at about 8.75 amperes, the latter purely as a protection against excessive power dissipation in the output transistors. This current figure, then, sets the limitation on available torque for a given motor. Even though the torque can be considerable - 875 oz-in for the PM-13510 motor for example - the current limitation may be removed by operating two or three power amplifiers in parallel in which case currents up to 20 or 30 amperes are reasonable, providing the power supply has this capability. This subject is covered in more detail in other Photocircuits technical literature.

The comments on the restrictions caused by generated motor back EMF indicate that it is possible to run out of control torque at high speeds long before the allowable amplifier peak current is reached. The only practical solution to this problem is to provide a higher voltage power supply. This can impose difficulties in the design of "protected" power amplifiers since the transistors must be able to hold off the supply voltage plus the back EMF voltage in the case of instantaneous motor current reversal at high speeds. Systems capable of operating in the range of ±30 volts are currently under development.

ACCURACY

It is apparent that one cannot specify the accuracy of an S-1 servo in terms of a simple number if one considers all the factors which would influence this number, and the fact that certain modifications are possible in order to meet a particular set of conditions. These points will be considered in the following sections.

Servo Gain - Stiffness

The essential parameter which controls the position or velocity stiffness or "accuracy" of the system when the shaft is subjected to torque loads and disturbances, is of course the loop gain of the servo. In our sample analysis system, which is typical, the conditions are described by Figure 10, for position, and Figure 11, for velocity.

In Figure 10, for example, we can see that for sinusoidal disburbances falling in the range from about 5 cps to about 250 cps we would expect a position "control factor" of 94 db; in other words there would be a peak to peak position displacement error of .00002 radians (approximately 4 sec of arc) for each oz-in of applied torque. This can be borne out in practice by applying a known torque load to the motor shaft and measuring the displacement of the trailing edge of the phase comparator square wave on an oscilloscope. Outside the 5 - 250 cps range, the stiffness is higher, so that if the above test is made with a DC (steady state) torque load, the curve shows the control factor to be about 112 db, due to the low frequency integrator circuit.

Velocity error determination, as illustrated in Figure 11, is a similar procedure except that velocity, being the time derivative of position, produces a curve with a nominal 20 db per decade slope, which points up the important fact that in order to determine (sinusoidal) velocity errors, the frequency of the disturbing torques must be known.

In accordance with the data developed earlier, it will be seen that the curves of Figures 10 and 11 will both be improved by roughly the increase in torque per ampere of larger motors compared with that of the 368 size, so that new stiffness factors may be readily predicted.

The "rounded peak" area of Figure 11 is interesting in that it shows clearly the frequencies where there is minimum velocity correction, indicating that torque disturbances in this range should be avoided if possible if instantaneous velocity (as opposed to position) is the important parameter in a given application. We have shown how this value of "maximum mechanical velocity impedance" may be calculated directly - often useful information in the early stages of system design.

Mechanical Tolerances

Most of the misunderstandings concerning S-1 Servo accuracy and indeed the system errors themselves can be traced to the subject of mechanical tolerances. The primary reason for this is that the feedback control signal is derived from the instantaneous position of the lines on the optical disc and not the peripheral surface of the motor shaft. If it is this surface which we are trying to control accurately, as is the case when pulling magnetic tape, as a critical example, then we are in trouble if the disc is not mounted concentrically on the shaft since it no longer represents true shaft position. A second and separate problem, also vital in tape capstan systems, is the tolerance allowed on the run-out of the shaft itself.

An interesting observation may be made by running a low inertia system and monitoring the phase comparator square wave on an oscilloscope. If the optical disc is purposely mounted eccentrically, the effect cannot be observed since the servo is able to control the position of the disc while the shaft is actually speeding up and slowing down on a sinusoidal once-per-revolution basis. If, now, we readjust the system for use with a large balanced flywheel and run the motor (unloaded) at a speed high enough so that the flywheel "takes over", then the results of the eccentricity are readily apparent - the large flywheel inertia "forces" the shaft to run at constant speed, and the lines of the disc move back-and-forth (speed up and slow down), also on a sinusoidal once-per-revolution basis, against the will of the servo amplifier. If the inertia is large enough, it is actually possible to make a rough quantitative measurement of the disc eccentricity by this means. The effect observed on the oscilloscope is identical to that of an external sinusoidal torque disturbance.

The effects of shaft run-out when pulling tape are similar, but are often more difficult to control in practice, since the diameter, the controlling factor for a given run-out, is usually smaller than that of the disc.

Three alternatives are available to control this situation: one can accept standard disc concentricity and shaft run-out tolerances which are reasonable from a production point of view, and result in a system with excellent accuracy specifications. For more critical applications, the tolerances can be tightened up with some increase in cost. For the most critical systems where necessary tolerances would be unreasonable, it is possible to use two optical pick-off systems mounted on opposite edges (180° apart) of a single glass disc such that when the outputs are connected together in parallel, one signal is leading while the other is lagging thus producing an error cancellation effect. This technique is common practice in very sophisticated optical systems, but of course adds to the cost of the S-1 package.

It should be pointed out here that the cumulative line-to-line spacing errors on the glass discs themselves are insignificant (less than 1/2 second of arc) compared to reasonable mechanical centering and electronic amplifier-limiter techniques, and thus can be ignored for all practical purposes. In addition, there is some error integration present since the optical system is always "looking at" a segment of the disc which contains many lines.

Some quantitative data on the effects of mechanical tolerances with respect to position and velocity errors are given in the next two sections.

Position Errors

The simplest and most effective tool for making measurements on the behavior of an S-1 system under various load conditions, (exclusive of the mechanical tolerance problems covered in the last section), is a display of the phase comparator square wave pattern on an oscilloscope. It should be clearly understood at the outset, however, that the back-and-forth movement of the trailing edges of the waves represents only the peak-to-peak position excursions from the nominal; there is no information in this display concerning the rate or frequency of the motion, therefore no deductions can be made as to the instantaneous velocity errors or "flutter" content. Since we are, however, looking at a time display, this motion is sometimes referred to as the "time displacement error" (T.D.E.) of the system.

Experiments of this nature with various torque loads will reveal as expected that the position deviation is proportional to the load torque, and changes with load frequency to the extent indicated by the system position response curve. The angular deviation will be seen to be independent of motor speed for a given load since the servo loop gain remains constant.

In addition, the amplifier will always go into saturation at some point before all of the available conduction angle (positive or negative) is used up. This insures that the full torque capability of the system in the linear region is available at any disturbing frequency before the motor position shifts out of the synchronous range.

Actual measurements of position accuracy are made by noting the peak-to-peak motion of the square wave under the load conditions of interest. If using the 5000 line track, for example, the synchronous range is one cycle of the pick-off signal which is 1/5000 of a revolution, meaning that the shaft has only this small angle to "move around in" under load and still remain in synchronism. Note that this angle is not what we might call the maximum "resolution" of the servo, since the shaft is actually under tight control somewhere within this range. Under no load conditions it is entirely practical for the shaft to be held to within 1/40 of this angle at any speed within the design range, which is equivalent to 5 millionths of a revolution peak-to-peak. This number sounds (and is) awfully small, but the internal torque disturbances are small (negligible cogging) and the gain is high. Unfortunately, this accuracy figure does not reflect the effects caused by practical mechanical tolerances, as we have seen, so that in any practical system the mechanical tolerances and not the servo will be the limiting factor.

The relationships which may be used to determine peak-to-peak position errors for both optical disc eccentricity and shaft run-out are as follows:

Position error (p-p) $= \dfrac{TIR}{2\pi r} \times 10^6$ millionths of a revolution

or $= \dfrac{TIR}{r}$ radians

or $= \dfrac{TIR}{r} \times 2.06 \times 10^5$ seconds of arc

where TIR = eccentricity (total indicated reading)

r (radius) = 0.925 ins (5000 line optical disc)

= 0.825 ins (2000 line optical disc)

= 0.725 ins (720 line optical disc)

= motor shaft radius (for shaft run-out error)

Note that if shaft run-out is an important factor in a given application its error may add to or subtract from that contributed by the optical disc, depending upon the relative angular orientation of the two errors.

Position errors and normal production tolerances for various motors are given in the literature describing Standard S-1 Servo Systems.

Velocity Errors - Flutter

Earlier sections and the typical curve of Figure 11 describe the situation regarding velocity control in the S-1 system. The important point when considering velocity errors is that velocity must always include a time dimension and is, in this case, simply the rate of change of the position characteristics discussed in the last section. Obviously, then, we cannot assign a value to a velocity error unless we know something about the rate of change of the disturbance which is causing the error. Since external disturbances are very often obscure under actual running conditions, additional measuring equipment such as that generally used for measuring flutter in magnetic tape devices is sometimes required, if flutter information as such is of importance. It bears repeating that the more easily obtained position data is fortunately more often than not the ultimate factor of greatest concern.

There is no problem, however, in assigning a value to the velocity errors or "flutter" caused by mechanical tolerances since the frequency of the "disturbance" is always once-per-revolution of the motor shaft and the error is essentially sinusoidal. (As with position accuracy, it should be noted that the errors may add or subtract if both disc and shaft tolerances are included).

A general relationship which we can use to determine "worst case" flutter at any speed of interest if the frequency of disturbance is known, is given by

$$\%\ FL\ (p\text{-}p) = \Delta t \times 2\pi f \times 100$$

where FL is defined as $\Delta V/V$

Δt is the "time displacement error", which can be obtained directly by measuring the peak-to-peak time excursions on an oscilloscope display of the phase comparator square wave.

f is the frequency of disturbance.

For the special case requiring flutter data due to eccentricities alone, Δt and f in the above equation are related to the amount of eccentricity and the once-per-revolution period of the error, so that the new expression which follows may be derived.

$$\% \text{ FL (p-p)} = \frac{\text{TIR}}{r} \times 100$$

where TIR = eccentricity (total indicated reading)

r (radius) = 0.925 (5000 line optical disc)

= 0.825 (2000 line optical disc)

= 0.725 (720 line optical disc)

= motor shaft radius (for shaft run-out error)

Some important observations may be made from the above relationships:

1) % flutter is directly proportional to time displacement error (Δt) and the frequency (f) of the load disturbance (within the servo passband).

2) Time displacement error is inversely proportional to the frequency of the load disturbance.

3) In the last section we pointed out that absolute angular position errors are independent of motor speed implying that the ratio of the error to the period of the reference frequency (one cycle of the phase comparator square wave) is constant. If the motor speed is reduced, this cycle period will increase (lower reference frequency), therefore the error period (time displacement error, Δt) must increase in proportion. In other words, Δt is inversely proportional to motor speed. Applying this to the first expression we may conclude then, that % flutter is also inversely proportional to motor speed for a given load disturbance.

4) The second expression shows that % flutter is inversely proportional to shaft radius, indicating the desirability of using the largest practical shaft ("capstan") for minimum flutter due to run-out. As pointed out earlier, the optical disc radius is fixed, and in practice is usually much larger than the driving shaft.

The above points illustrate that accuracies of greatest concern (angular position, time displacement, or velocity, depending upon the application), can be largely controlled and improved by giving some careful thought in the design stages to the nature of the disturbances which are allowed to reach the motor shaft.

APPLICATIONS

Applications for the system described in this report are numerous and varied, but perhaps the widest use lies in the general area which we could categorize as "web drives". These usually involve the use of a Printed Motor or Minertia Motor as a direct drive capstan and include the movement and control of various media such as magnetic tape, paper tape, photographic film, textile products, etc. This general application includes not only the end use of these products but also some processes in the original manufacture as well. Typical is the coating of film and magnetic tape, where the requirement is to control large rolls of the base material.

Other photographic applications include the operation of focal plane shutters and the intermittent motion of film (one picture for each independently triggered revolution of the motor shaft) such as is required by some wide-angle aerial photography devices.

High speed high inertia drum drives of various types can be controlled by this system, and there are applications in the areas of optical measurement and spectrophotometry. The performance of oceanographic recording drives and facsimile transmission equipment have been greatly improved by means of the S-1 Servo concept.

Under investigation are the possibilities for including the servo in the manufacture of extruded materials such as wire and cable where synchronous motors are often employed.

In many of the above applications there is often a requirement to synchronize two or more shafts together on an absolute position pulse-for-pulse basis. The S-1 servo lends itself ideally to this situation since a single master reference may be used to control all shafts, or a master-slave relationship may be easily set up where the pick-off output from one device is used as the reference input for the next.

Although these applications by no means cover all possibilities, they may help to stimulate the imagination of those whose requirements include the precise control of rotating shafts with respect to angular position, timing accuracy, and velocity, on both a long term and an instantaneous basis.

CONCLUSIONS

The preceding sections have explored the various aspects of the Photocircuits S-1 synchronous phase lock servo design in sufficient depth to outline most of the important design parameters and to alert the designer to problem areas and basic system limitations. It is not possible to say whether or not the design of the particular system used in the sample analysis is optimum for any given application because there are so many factors extending beyond the domain of the servomechanism itself which influence the final result.

The study suggests fairly clearly, however, the various avenues which could be pursued in order to manipulate bandwidth, speed range, accuracy, torque capability, power handling, and mechanical tolerances in order to provide optimum performance for a specific case.

In conclusion, it is also clear that if the assumptions on loop gain, available driving torques, and torque disturbances are fulfilled, the system is capable of displaying a very high order of performance in comparison to other known means for executing the same functions.

PMI PRINTED MOTORS, INC.

GLEN COVE, NEW YORK

Engineering, Manufacturing and Sales by:

Photocircuits CORPORATION